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ABSTRACT

Technological advances during the past few decades have revolutionized many complex systems that influence human activity. As the rate of technological progress accelerates, these systems will become more complex, and new ones will evolve. Citizens in a technological society need to be able to make intelligent choices about how technology will affect their lives. This requires a better understanding of the technology itself; its potential and its limitations. This is a module for a course designed to introduce students, particularly those not majoring in the sciences or mathematics, to technological concepts. The fundamental concepts of two satellite-based radio navigation systems are presented in this module. The application to aircraft, boats, and automobiles is discussed. This module is appropriate for an introductory course in technology studies or the physical sciences. (CW)

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by Marian Visich, Jr.

The fundamental concepts of two satellite-based radio navigation systems are presented in this module. The application to aircraft, boats, and automobiles is discussed. The module is appropriate for an introductory course in technology studies or the physical sciences.

Designed to further student understanding of technological issues, this module is one in a series developed in a project on "Technology and the Liberal Arts," which is sponsored by CIC—the Council of Independent Colleges, Washington, D.C.

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Technological advances in just the past few decades have revolutionized many of the complex systems that guide our lives—the way we travel, for example, and how we communicate with one another, heal our sick, even the way we grow our food. As the rate of technological progress accelerates, these systems will become more complex, and new ones will evolve. Technology will continue to be a preeminent force in our lives.

As citizens in a technological society, therefore, we need to be able to make intelligent choices about how technology will affect our future lives. This requires that we have a better understanding of technology itself. We need to understand its potential and limitations. Further, we need to understand the very *process* of technology, and have a sense of its methodology and rules.

The Council of Independent Colleges has been deeply involved in these issues since 1984, in a project entitled "Technology and the Liberal Arts." Working with faculty from small liberal arts colleges, CIC has sought to integrate the study of technology and technological issues into the liberal arts curriculum. Our goal is to improve the understanding of technology on the part of undergraduate students—the future citizens of the technological society.

This course module is one in a series developed in the CIC project under a grant from the Exxon Education Foundation. Each module is designed to introduce students, particularly those not majoring in the sciences, to a technological issue or concept. In the process of completing the exercises in the modules, we also hope students will develop an idea of the methodology of technological inquiry. Our goal in publishing the modules is to make teaching materials available for use in courses across the liberal arts disciplines. We are deeply indebted to the Exxon Education Foundation and its executive director, Arnold R. Shore, for supporting this endeavor.

I want to also acknowledge the many college faculty who have participated in CIC's technology project. To each, I offer my sincere thanks for pioneering the important effort to bring technology into the mainstream of the curriculum.

Allen P. Splete
President
The Council of Independent Colleges
October 1987

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Navigation By Satellite

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INTRODUCTION

On September 1, 1983, Korean Airlines Flight 007 left Anchorage, Alaska for Seoul, Korea. During the flight, the Boeing 747 strayed off course by almost 300 miles. The Korean airliner flew over Soviet Union airspace and was shot down by a Russian air-to-air missile near Sakholin Island. A total of 269 passengers and crew members were killed when the Korean airliner was shot down.

The Korean airliner was equipped with three independent inertial navigation systems. In an inertial navigation system (INS), the acceleration (i.e., the rate of change of velocity with respect to time) of the system is measured in three directions by accelerometers which are stabilized by gyroscopes. The three accelerometers are placed on a stable platform so their sensitive axes constantly point north, east and towards the center of the Earth, respectively. The information from the accelerometers and gyroscope is fed into a navigation computer which determines

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the vehicle's position and velocity.

When an inertial navigation system is first turned on, the precise location of the vehicle must be entered into the navigation computer. This is extremely important since the computer determines the motion of the vehicle relative to its initial position. In addition, the accelerometers and gyroscopes must be aligned and stabilized before they are used for navigation. This process can take up to 30 minutes depending upon the system. When using an inertial navigation system for a long period of time, the location of the vehicle must be updated using other navigation methods to account for system inaccuracies. The position accuracy of typical commercial inertial navigation systems used on transoceanic airliners is approximately one mile for every hour of flight.

Each of the inertial navigation systems on the Boeing 747 can provide navigation to nine enroute waypoints along a Great Circle Route. The Great Circle Route is the shortest distance between two points on the surface of the Earth. It is the circle on the surface of the Earth formed by passing a plane through the center of the Earth which divides it into two equal parts. The latitude and longitude of the waypoints must be entered into the system by the navigator. Although the navigation data could be entered into all three systems from the keyboard of any one of the inertial navigation systems, most experienced navigators enter the data into each system to provide a cross check on each other. When coupled with the aircraft's autopilot, the inertial navigation system will guide the airliner to successive waypoints automatically. It is theorized that the longitude of Anchorage, Alaska was entered as W139 instead of W149 into the INS which controlled the autopilot of Korean Airlines Flight 007. This meant that as far as the INS was concerned, the flight was initiated 300 nautical miles to the east of the airport runway.

Land-based radionavigation systems are frequently used to update the location of a vehicle using INS. The distance of an aircraft or boat from a land based transmitter can be determined by measuring the time it takes for a radio signal to travel from the transmitter to the vehicle and multiplying it by the speed of light. In the case of marine applications, the boat would be located somewhere on a circle on the Earth whose center is at the transmitting station and whose radius is equal to the distance from the transmitting station. If radio signals are transmitted from three land-based transmitters at the same time, the location of the boat would be at the intersection point of the circles from the three transmitters.

For aeronautical applications, the location of an aircraft from a given transmitter would be somewhere along a sphere whose center is at the transmitter and whose radius is equal to the distance to the transmitter. The position of the aircraft would then correspond to the intersection point of three spheres.

Loran (Long Range Navigation) and Omega are radionavigation systems in operation today. Loran covers approximately 10 percent of the surface of the Earth, extending about 1000 miles from the shoreline where the transmitters are located.

The entire coastline of the United States is covered by Loran. Loran transmitters broadcast signals at approximately 100,000 Hertz (cycles per second). At this low frequency, the radio signals bend around the Earth. The navigation accuracy of Loran is between 250 and 500 feet for marine applications. However, the system has the ability to allow a boat to consistently return to the same spot on the ocean to within 50 to 75 feet. Loran is the most common marine navigation system in use today. If the Korean airliner was equipped with a Loran receiver, it could have obtained full route coverage from Alaska to Japan with an accuracy of five miles.

Omega provides 90 percent coverage of the Earth with position accuracy of 6,600 feet for marine applications and within four miles for airline operations. To obtain worldwide coverage, the radio navigation signals are transmitted at approximately 10,000 Hertz. At this very low frequency, ground radio waves may propagate for distances as great as 8000 miles. Over 1,500 commercial aircraft are equipped with Omega radionavigation systems as back-up for their inertial navigation systems. Unfortunately, the Korean airliner did not carry an Omega system. The book *Dutton's Navigation and Piloting* by Elbert S. Maloney, is an excellent reference book on marine navigation and contains detailed information about the Loran and Omega radionavigation systems.

In this module, the description and applications of two satellite-based radionavigation systems are presented. The Transit Navigation Satellite System is presently in operation by the United States Navy and has the capability of providing worldwide navigation service with the same accuracy as the Loran system. When operational in the 1990s, the United States Air Force's Navstar Global Positioning System will have the potential of providing worldwide service with an accuracy on the order of tens of feet. Both systems can be used to update inertial navigation systems on all types of vehicles.

Transit Navigation Satellite System

Background

During the 1960s, the Polaris submarine fleet was one of the main elements of the strategic defense system of the United States. One of the limitations of the Polaris submarine was that it depended upon an inertial navigation system for guidance. Although the inertial guidance system was very accurate, it required periodic updates through celestial observations or line of sight bearings. This required that the Polaris submarine surface for long periods during inclement weather such as in the polar regions and risk the chance of being located. The Transit system was developed to provide accurate position updates for the inertial guidance system aboard the Polaris submarines.

After the launch on October 4, 1957 of the first artificial satellite, the Russian Sputnik I, Drs. William H. Guier and George C. Weiffenback of the Applied Physics

Laboratory (APL) of Johns Hopkins University measured the large frequency variation of the radio signal from Sputnik I as it travelled in its orbit. The frequency variation, known as the Doppler shift, depended upon the relative velocity between the satellite and the receiving station. The Doppler shift is the reason for the apparent change in the pitch of a whistle of a speeding train at a railroad crossing or of a siren on an ambulance as it passes an observer. The pitch of a whistle or siren appears to be higher than the actual pitch as it approaches the observer and appears lower as it moves away.

Drs. Guier and Weiffenback made extensive measurements of the Doppler shift from Sputnik I and developed algorithms for determining the orbit of the satellite from measurements at a single receiving station. Drs. Richard B. Kershner and Frank T. McClure, also research scientists at the Applied Physics Laboratory, became interested in the inverse problem; namely, the determination of the location of a receiver on the surface of the Earth by measuring the Doppler shift of a radio signal from a satellite in a known orbit. The solution of the inverse problem is the basis of the United States Navy's Transit Navigation Satellite System, which was funded in 1958.

Dr. Kershner was given the responsibility for the development of the Transit system. This included the design of the navigation satellites, the modeling of the gravitational field of the Earth to permit the accurate determination of the orbit of a satellite orbiting the Earth and the development of shipboard equipment for navigation purposes. In 1963, the destroyer USS Hazelwood was the first Navy ship to navigate using signals from an orbiting satellite. In 1964, the nuclear-powered guided- missile cruiser USS Long Beach used the Transit navigation system on its around-the-world cruise. After testing of navigation equipment on Polaris submarines and aircraft carriers, the Transit navigation system became operational in late 1964. Since the system was developed for updating the inertial guidance system of the Polaris submarine fleet, it was only available for military operations. On July 29, 1967, Vice President Herbert Humphrey announced in a speech at Bowdoin College that the Transit navigation system was being made available to private users. In his comments he stated that the Transit navigation system had "enabled fleet units to pinpoint their position anywhere on Earth. The same degree of navigational accuracy will now be made available to non-military ships."

System Description

The satellites used in the Transit Navigation Satellite System were launched from Vandenberg Air Force Base into polar orbit by the Scout rocket. They are located in circular orbits 762 miles above the surface of the Earth and complete one orbit in 107 minutes (Figure 1). At an altitude of 762 miles, a satellite is in the line of sight of boats located within 2,200 miles of the point on the surface of the Earth directly below the satellite. All of the boats in this region can use the signals broadcast by the satellite to obtain navigation fixes.

Figure 1 — Transit Navigation System satellites in circular, polar orbits about 672 miles above the Earth.

In April, 1986, there were seven Transit Navigation System satellites in orbit around the Earth. Figure 2 shows the north polar view of the location of the orbital planes of the Nova and Oscar satellites on April 1, 1986. Due to the non-spherical nature of the Earth's gravitational field and the influence of the Moon and the Sun on the motion of the satellites, the orbital planes of the satellites move (precess) relative to each other, changing the system configuration. The precession rates of the satellites are shown in Figure 2 in degrees per day. The Oscar 24 satellite is currently stored in orbit as a spare and does not transmit navigation messages.

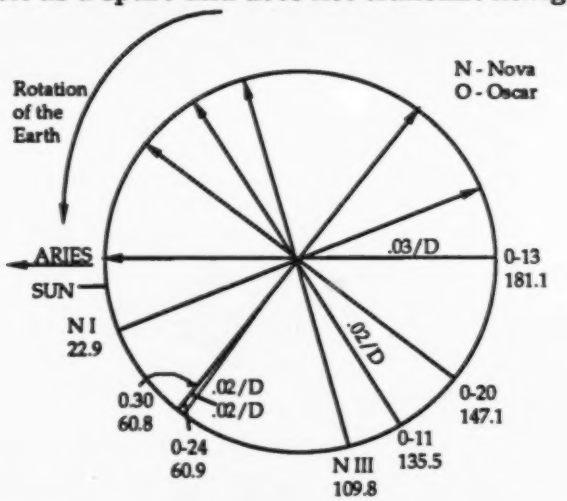


Figure 2 — Orbital planes of Transit Navigation System satellites on April 1, 1986 (North Polar View)

The Oscar satellites (Figure 3) were developed in the early 1960s by the Applied Physics Laboratory. The main body of the satellite is an octagonal prism 10 inches high and 18 inches across the flats. The satellite is stabilized by a 75-foot self-erecting boom with a 3-pound weight at the end of the boom. The boom extends from the top of the satellite and ensures that the "lampshade" directional antenna mounted at the bottom of the satellite always faces the Earth. Four solar panels supply electrical energy for the transmitting system on the satellite. The computer memory on the satellite stores navigation messages relayed by ground stations twice daily. The computer memory can store up to 16 hours of navigation messages.

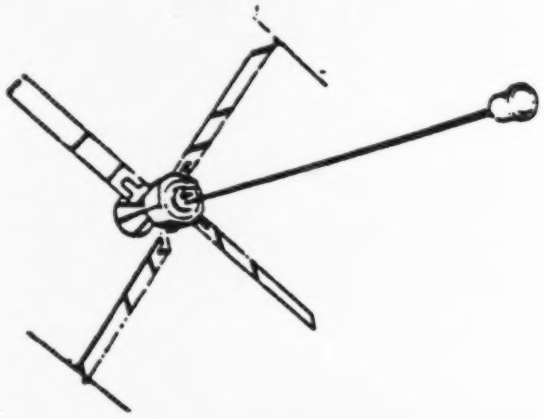


Figure 3 — Oscar navigation satellite

During the mid-1970s, the Applied Physics Laboratory launched two proof-of-concept TIP (Transit Improvement Program) navigation satellites into polar orbit. The TIP satellites were designed with increased transmitting signal strength and reliability and with a disturbance compensation system (DISCOS). The velocity of a satellite in orbit around the Earth is affected by aerodynamic drag and solar radiation pressure. In the DISCOS system, a mass is suspended electromagnetically inside the spacecraft and is free to move only in the flight direction. Since the mass is shielded from the aerodynamic drag and solar radiation pressure acting on the satellite, it travels along a drag-free orbit. The position of the mass relative to the interior of the spacecraft is determined optically and a small rocket propulsion system is fired intermittently to maintain the same relative position between the mass and the spacecraft. As a result, the TIP satellite followed a drag-free orbit. An on-board computer, which was programmable from the ground, had two memory units. The capacity of each memory unit was large enough to store five days of navigation messages. Although the solar panels did not fully deploy on both satellites, the proof-of-concept experimental program was successful. The Navy authorized RCA Astro-Electronics to build three satellites, renamed Nova, based on the TIP design. Nova I was launched on May 15, 1981 and Nova III on October 11, 1984. Nova II remains as an on-ground spare.

In order to determine the location of a receiver on the surface of the Earth using the Transit navigation satellite system, the location of the satellites in space must be known precisely as a function of time. An error in the location of the satellite transmitting the navigation signal would result in a corresponding error in the location of the receiver. The orbit of a satellite is affected by small perturbation forces such as the non-spherical gravitational forces of the Earth, atmospheric drag, solar radiation, and the gravitational effects of the Sun and the Moon. As a result, the orbital parameters stored in the memory of the satellite must be continuously updated.

The operation of the Transit Navigation Satellite System is the responsibility of the Navy Astronautics Group at Point Magu, California. Satellite tracking and injection (relay) states are located at Prospect Harbor, Maine; Rosemont, Minnesota; and Wahiawa, Hawaii. When a satellite passes over a tracking station at a known location, the Doppler shift of the satellite signal is used to determine the exact position of the satellite in space. The Doppler shift data from all of the tracking stations is forwarded to the computing center at Point Magu (Figure 4) which computes the orbit of the satellite as a function of time. The orbit of the satellite is then determined for the next sixteen hours in two-minute intervals based on Universal Time from the Naval Observatory. The new orbital parameters are then sent to one of the injection (relay) stations for transmission to the memory of the computer on the satellite. Orbital updates are transmitted to the Oscar satellites approximately every 12 hours. The orbit of the Nova satellite is much more stable than that of an Oscar satellite because of the disturbance compensation system on it. Since the perturbation effects of atmospheric drag and solar radiation are eliminated, orbital updates are transmitted to the Nova satellites approximately once a week.

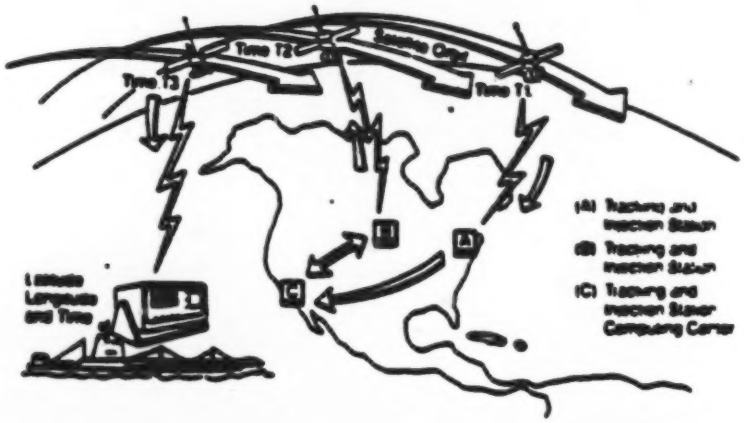


Figure 4 — Tracking stations at Prospect Harbor, Maine (A). Rosemount, Minnesota (B), and Navy Astronautics Group Headquarters at Point Mugu, California (C). Tracking station at Wahiawa, Hawaii, not pictured.

System Operation

The Doppler frequency change of a radio signal from a source moving relative to a receiver is given by

$$\Delta f = (V/C)\, f_T$$

where V is the relative velocity between the source and the receiver, C is the velocity of light and f_T is the frequency of the transmitted signal from the source. The relative velocity is positive as the source approaches the receiver and negative as the source moves away from the receiver. In the case of the receiver on Earth and the source on an orbiting satellite, the relative motion between the two is complex. The satellite is moving in an orbit around the Earth, the Earth rotates beneath the orbit of the satellite and the receiver can be moving relative to the Earth as, for example, on a boat. As a Transit navigation system satellite moves toward a receiver on land or on the ocean, the frequency of the received signal is higher than the transmitted signal. When the satellite is at its closest point of approach to a receiver, the frequency of the received signal is equal to that of the transmitted signal. As the satellite moves away from the receiver the frequency of the received signal decreases.

The Oscar and Nova satellites broadcast radio signals at two frequencies: 149.988 MHz (million cycles per second) and 399.968 MHz. The transmitted signals are extremely stable with an error of no more than one part in 100 billion during a satellite pass of approximately 20 minutes. Every two minutes, beginning and ending at every even minute, the satellite broadcasts a binary message which contains precise orbital data and a timing mark. The last 25 bits of the binary message represent a timing mark and the start of another two-minute message. The mes-

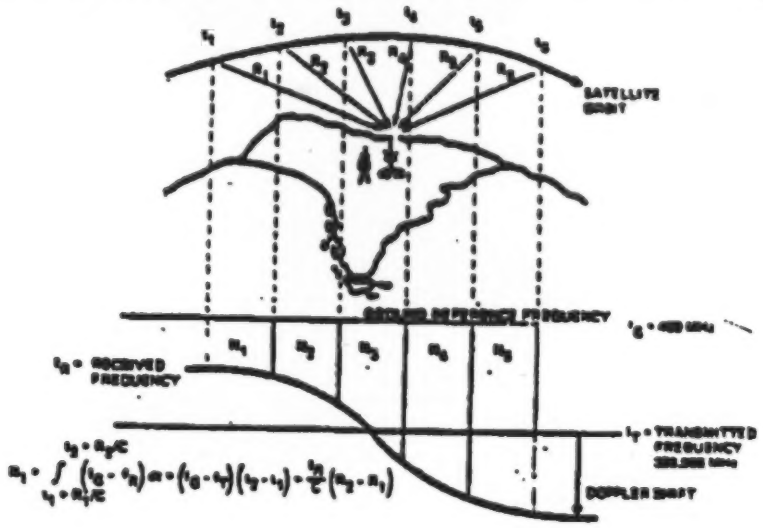


Figure 5 — Satellite Fix Determination

sage also includes the identity of the satellite transmitting the message.

For a single-channel receiver, only the higher-frequency signal transmitted from the satellites (399.968 MHz) is used to determine the receiver location. The receiver has a built-in oscillator which generates a ground reference signal of 400.000 MHz. The receiver measures the difference in frequencies between the received signal (f_R) and the ground reference signal (f_G). When the satellite reaches the closest point of approach, the difference ($f_G - f_R$) would be 32 KHz (thousand cycles per second) (Figure 5). Due to the Doppler shift of the transmitted signal (f_T) as the satellite moves relative to the receiver, the frequency difference can be as low as 24 KHz as the satellite approaches the receiver and as high as 40 KHz as it recedes.

The Doppler count (N) is defined as the number of different frequency cycles counted by the receiver between two timing marks from the satellite. It is related to the difference in range (or distance) of the satellite to the receiver when the satellite transmitted the two timing marks as given below:

$$N_1 = (f_G - f_T)\ (t_2 - t_1) + (f_G/C)\ (R_2 - R_1)$$

where R_1 the range of the satellite at the timing mark t_1

R_2 the range of the satellite at the timing mark t_2

C is the speed of light

During a given satellite pass, the receiver calculates a series of range difference ($R_2 - R_1$, $R_3 - R_2$, etc.). With the orbital data from the satellite, a microprocessor on a stationary receiver determines the best intersection point of the ranges and the satellite orbit. To decrease the microprocessor computing time, an approximate location of the receiver is entered into the microprocessor to initiate the calculations. For a moving receiver, the motion of the receiver during the satellite pass must be entered into the receiver to obtain accurate navigational results.

Between five and eight Doppler count measurements can be made over a period of 10 to 16 minutes during a satellite pass over a receiver. During this period of time, the satellite travels between 2,700 and 4,400 miles. The average time interval between satellite passes with a six operational satellite system varies from 35 to 100 minutes—the higher the latitude, the shorter the time between satellite passes. Accurate navigation data can only be obtained when a satellite is located between 15 and 75 degrees above the horizon from the receiver.

During daylight, solar radiation produces a belt of ionized particles in a region 40 to 300 miles above the surface of the Earth known as the ionosphere. Radio waves passing through the ionosphere are slowed down due to the presence of free electrons. The change in velocity of the radio waves is a function of the frequency of the transmitted signal. By transmitting signals at different frequencies from a

satellite and comparing their Doppler shifts, the effects of the ionosphere can be greatly reduced. The satellites of the Transit navigation system broadcast signals at both 149.988 and 399.968 MHz for this purpose.

The position fix error for a stationary receiver is a function of the receiver design, the accuracy of the navigation data transmitted from the satellite and the effect of the atmosphere on the signal as it passes through it. This error can be obtained from the scatter of locations determined from many passes of Transit system satellites for the receiver at a fixed location. For a dual-channel receiver measuring both signals from a satellite, errors between 27 and 37 meters (88 and 120 feet) are typical. Single channel receivers (399.968 MHz) used for marine applications have typical errors between 80 and 100 meters (260 and 330 feet) which includes the effect of ionospheric refraction.

Another source of error is due to the error in measuring the velocity of a moving vehicle on which the receiver is located during the period when the satellite frequency measurements are made. Typical errors for marine receivers on moving boats are 0.2 nautical miles (1200 feet) in location for every knot (1.15 miles per hour) or northward velocity error.

Applications

The two major applications of the Transit Navigation Satellite System are for marine navigation and for determining the exact location of a fixed point on the surface of the Earth. Magnavox has been a leader in the development of Transit satellite navigation receivers since 1967. The development of microelectronics has had a major impact on the evolution of Magnavox marine receivers and is discussed in the Magnavox booklet *The Transit Satellite System* by Thomas A. Stansell. In 1968, only dual-channel receivers were available from Magnavox. The receivers used a large minicomputer and an electromechanical teletype for output. Single-channel receivers were introduced in 1977 along with small microcomputers. In 1973, the compact video terminal replaced the noisy teletype. A cassette tape reader was used for loading the computer program. By 1976, with the development of microprocessors, Magnavox receivers were reduced to a single small unit with increased capacity and reduced cost. In this section, the application of satellite receivers for marine navigation and fixed point positioning will be discussed.

The main advantages of using the navigation system for marine navigation are that it can be used anywhere in the world anytime a satellite is overhead, it works equally well in all types of weather and its accuracy is competitive with short range radiolocation systems such as Loran. The main disadvantage is that satellite fixes can only be obtained every 35 to 100 minutes depending upon the latitude of the receiver. Increasing the number of satellites in orbit would decrease the time between satellite passes at a given latitude.

The Navy Astronautics Group has estimated that by the end of 1986, 80,000 marine satellite navigation receivers were installed on commercial and private boats. This corresponds to an annual growth of 46 percent since 1974, when only 600 units were in operation. During the same period of time, the cost of receivers decreased from approximately $30,000 in 1974 to less than $2,500 in 1986.

The typical 1986 marine navigation satellite receiver provides the captain of a boat with sufficient navigation information to cruise around the world. In addition to determining the latitude and longitude of the boat during a satellite pass, the navigation satellite receiver can provide latitude and longitude readings between satellite passes based on the dead reckoning mode. In this mode, the boat's approximate position is determined by the receiver from its last known position using .compass and speed data from instrumentation on the boat. The navigation error due to dead reckoning is corrected during the navigation fix when the next satellite passes over the receiver. The Transit satellite receiver can also be coupled with either a Loran or Omega radionavigation receiver to provide navigation data between satellite passes. The radionavigation systems provide greater accuracy than the dead reckoning mode, but at an additional cost of between $1,000 and $2,500.

Some of the other features of a typical marine navigation satellite receiver are:

- display of Greenwich Mean Time (GMT) and Dead Reckoning Time (DRT) since the last satellite fix

- distance and bearing to 15 way points to final destination via Great Circle or Rhump Line Routes[1]

- memory recall of last position and time of satellite fix prediction of future satellite passes

- automatic acquisition and tracking of optimum satellite when more than one satellite is above the boat's horizon at the same time

- power-saving mode, which reduces power required by receiver between satellite passes.

The Transit Navigation Satellite System can also be used for geodetic surveying, accurately positioning of off-shore oil rigs and geophysical exploration. In the point positioning method, a receiver at a given location records the Doppler frequency shift of all of the satellite passes over an extended period of time. The data from all of the satellite passes is fed into a computer to determine the location of the receiver in three dimensions—latitude, longitude and altitude. Position accuracy of six meters (20 feet) can be obtained with 10 satellite passes and four meters (13 feet) with

[1]In a Rhump Line Route, a boat maintains a constant heading (compass reading) from its starting point to its destination.

25 satellite passes. To obtain a position fix using the data from 25 satellite passes requires approximately 16 hours at the higher latitudes and 40 hours in the vicinity of the equator.

In the differential positioning or translocation method, two receivers are used: one at a known location and the other at a point whose location is to be determined. Both receivers measure the Doppler frequency shift from the same set of satellite passes. The data from both locations is fed into a computer which solves for the differential position between the two points. Using this technique, the location of an unknown point can be determined within 76 centimeters (2.5 feet).

Prior to the Challenger disaster in January, 1986, the Navy had planned to deactivate the Transit Navigation Satellite System sometime in the mid-1990s after the Navstar system was fully operational. The nine on-ground spare satellites—eight Oscar satellites and one Nova satellite—were scheduled to be placed in service as the present satellites in orbit failed. Although the design life of an Oscar satellite is less than ten years, the Oscar 13 satellite has been operating in orbit since May, 1967. The operational Navstar satellites were scheduled to be launched by the Space Shuttle starting in mid-1986. Since the Space Shuttle will not be operational until sometime in 1988, the Navy is considering launching the nine on-ground Transit navigation system satellites using NASA Scout launch rockets over the next several years to increase the capability of the present system. This would result in a decrease in average time between satellite passes at all latitudes.

Navstar Global Positioning System

Background

The Transit Navigation Satellite System became operational in 1964 and provided the United States Navy with accurate two-dimensional navigation (latitude and longitude) for their surface vessels and submarines. The major disadvantage of the system was that it could only be used for the navigation of a vessel when a Transit satellite was in line-of-sight with the vessel. With a five-satellite system, the average time between navigation fixes varied between 35 and 100 minutes depending upon the latitude of the vessel.

During the 1960s, the Air Force and the Navy conducted studies on advanced space-based navigation systems with increased capabilities. The Navy system was an upgraded two-dimensional system known as Timation (Time Navigation). It was a passive radio navigation system based on the satellite atomic clock technology developed by the Naval Research Laboratory.

The Air Force navigation system was designated as Project 621B and was to provide continuous world-wide coverage to aircraft. In the proposed system, naviga-

tion data and timing signals from ground stations on Earth would be relayed by orbiting satellites to aircraft for navigation fixes.

In April, 1973, the Secretary of Defense designated the Air Force as the executive service of a joint services program to develop a comprehensive navigation system that would satisfy the vast majority of the Department of Defense positioning and navigation needs. Among the design requirements for the system were:

- accuracy: position in three dimensions
  16 meters (52 feet),
  velocity in three dimensions
  0.1 meters/sec (.3 feet/sec),
  time 100 nanoseconds (billionths of a second)
- continuous worldwide all weather day/night coverage
- passive and silent
- unlimited number of authorized users
- user not required to have a precision atomic clock
- capable of denying high accuracy to unauthorized users
- high jamming resistance in wartime

In December, 1973, the Defense System Acquisition Review Council (DSARC) decided to proceed with the development of the joint services program and cancelled both Timation and Project 621B. The new system was designated the Navstar (Navigation Satellite Timing and Ranging) Global Positioning System (GPS). The responsibility for managing the Navstar program was assigned to the Air Force Systems Command's Space Division in Los Angeles. A Joint Program Office (JPO) with representatives of the military services, the Defense Mapping Agency and the Department of Transportation, has the overall responsibility for the development of the system.

To obtain a three-dimensional position and velocity fix, a user must be in the line-of-sight of at least four satellites simultaneously. The original GPS design called for eight satellites in each of three orbital planes for a total of 24 operating satellites as shown in Figure 6. The satellites would be equally spaced in circular orbits 12,500 miles above the surface of the Earth and complete one orbit in 12 hours. Each orbital plane would be inclined 63° with respect to the equator and separated by 60° in longitude. With this satellite configuration, over six satellites would be visible at any time at any place on Earth.

In 1978, four prototype (Block I) Navstar satellites were launched into circular orbits 12,500 miles above the Earth as part of the concept validation phase in two different orbital planes. Due to budgetary restraints in 1979, the Department of Defense reduced the budget of the GPS program by $500M and reduced the number of satellites in the fully operational system from 24 to 18. After an extensive study, the JPO determined that the optimum orbital configuration for 18 satellites would be three satellites in each of six orbital planes as shown in Figure 7. Each orbital

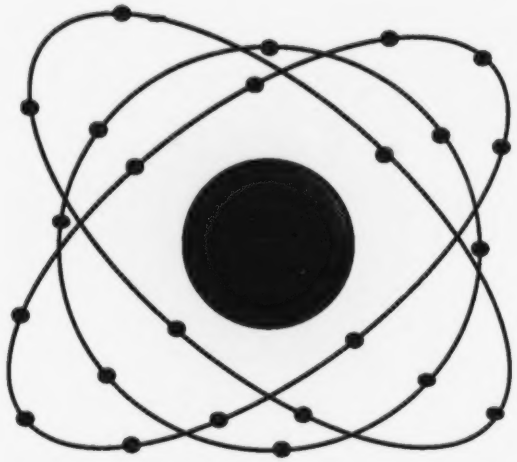


Figure 6 — Original GPS satellite configuration: 24 satellites in 3 orbital planes.

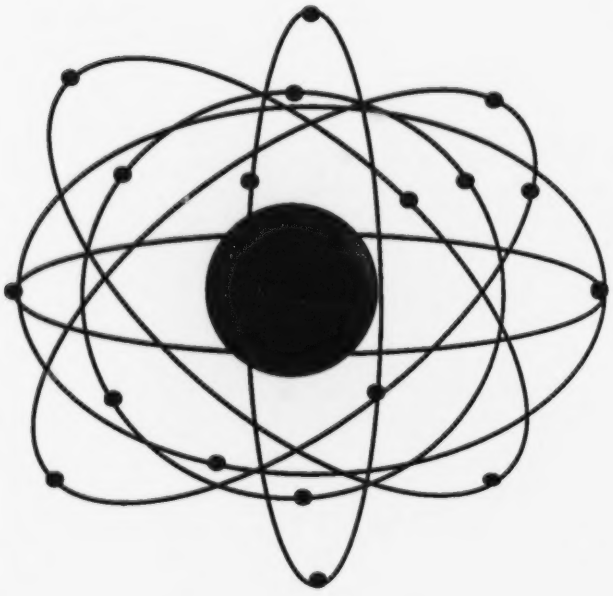


Figure 7 — Operational GPS satellite configuration: 18 satellites in 6 orbital planes.

plane would be inclined 55° with respect to the equator and separated by 30° in longitude. With this configuration, there would be small regions on the Earth which would not be continuously in the line-of-sight of four satellites. During the period when four satellites are not in view of an aircraft, the aircraft would have to depend upon a back-up system, such as an inertial navigation system, to provide continuous coverage.

When the Navstar navigation satellite program was initiated in December, 1973, it was planned that the system would be fully operational in 1984. Due to the budget reduction in 1979 and program slippage, it was estimated in 1980 that the GPS system would have two-dimensional navigation capability in 1987 with 12 satellites and full three-dimensional capability by the end of 1988.

The operational Navstar satellites were designed to be launched by the Space Shuttle starting in 1986. During the period 1986-1988, Navstar satellites were scheduled to be the single most frequent payload to fly on the Space Shuttle. Unfortunately, on January 28, 1986 the Space Shuttle exploded 73 seconds after the launch of Mission 51-L, killing seven astronauts. As a result of the required redesign of the solid propellant booster rocket for the Shuttle, NASA has projected that the next flight of the Space Shuttle will take place during the first quarter of 1988 or even later. Due to the destruction of the Challenger reducing the number of orbiters to three, there will be an extensive backlog of both military and commercial satellites waiting to be launched over a period of several years.

After the Challenger disaster, the Air Force made the launching of the Navstar satellites to build up an operational GPS system one of its highest priorities. In January 1987 the Air Force selected the McDonnell Douglas Corporation to build 7 medium launch vehicles (MLV), with an option for 13 additional MLV boosters, to launch the Navstar satellites. The first satellite is scheduled to be launched in October, 1988. The schedule of the remaining launches would be 6 in 1989, 7 in 1990, and 6 in 1991. Based on this launch schedule, the three dimensional navigation capability would not be available until the mid-1990s.

System Description

The Navstar Global Positioning System is a space-based radio navigation system with the capability of providing three dimensional position and velocity information to users. As shown in Figure 8, the GPS system consists of three separate segments: a space segment, a control segment, and a user segment.

Figure 9 presents the evolution of the three segments based on a full operational capability by the end of 1988. The Navstar program is being developed in three phases: Phase I, Concept Validation Program; Phase II, Full Scale Development and Test; and Phase III, Full Operational Capacity.

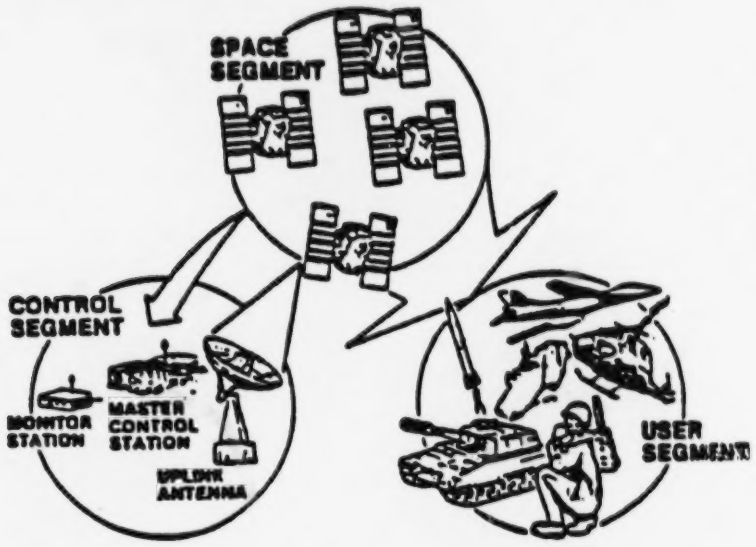


Figure 8 — GPS system operation

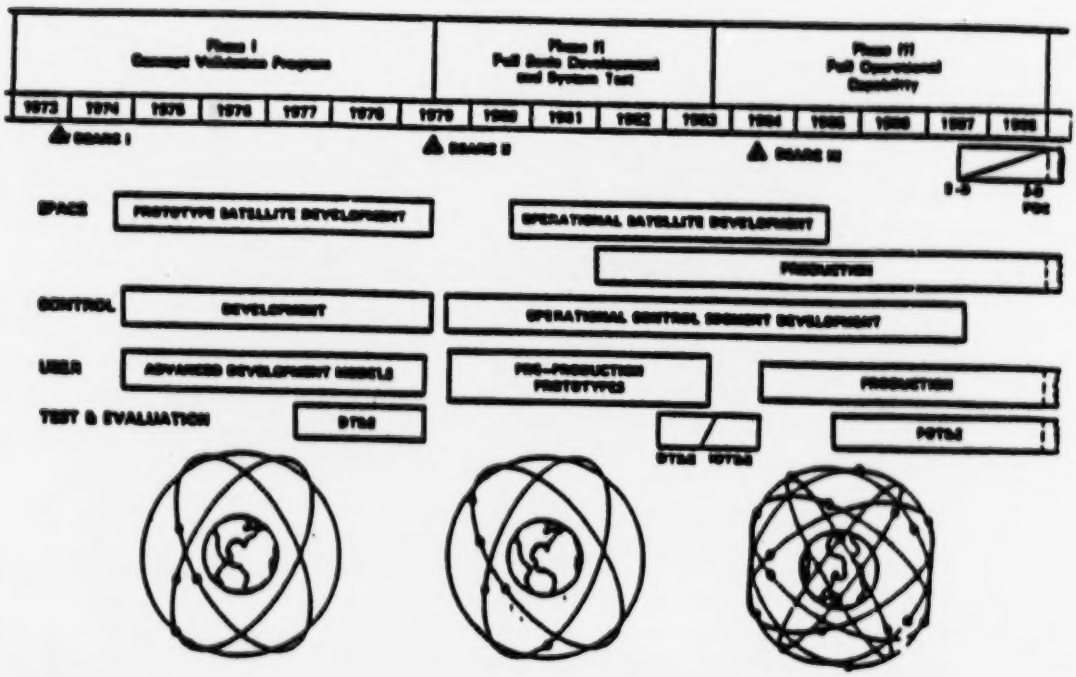


Figure 9 — GPS program schedule

In order to validate the GPS concept, Rockwell International's Satellite Systems Division was given a contract in 1974 for the construction of 11 prototype Navstar satellites. The satellites were launched over the period February, 1978 to October, 1985, from Vandenberg Air Force Base in California, using the Atlas F launch rocket. Navstar VII was destroyed shortly after leaving the launch pad due to a rocket failure. In December, 1986, there were eight prototype satellites providing navigational signals to users. The other two satellites in orbit are inoperative due to problems with their atomic clocks. The eight operational prototype satellites are located in 12,500 mile circular orbits in two orbital planes—four in each plane. The eight satellites provide a "window" of about seven hours a day when the GPS signals are useable for position fixing. The prototype satellites enabled engineers to validate the GPS concept and its design accuracy.

In March, 1983, Rockwell International was awarded a $1.17 billion contract for the construction of 28 operational (Block II) satellites. The delivery schedule for the satellites is

1986 - 4 satellites, 1987 - 8 satellites,

1988 - 9 satellites, 1989 - 7 satellites.

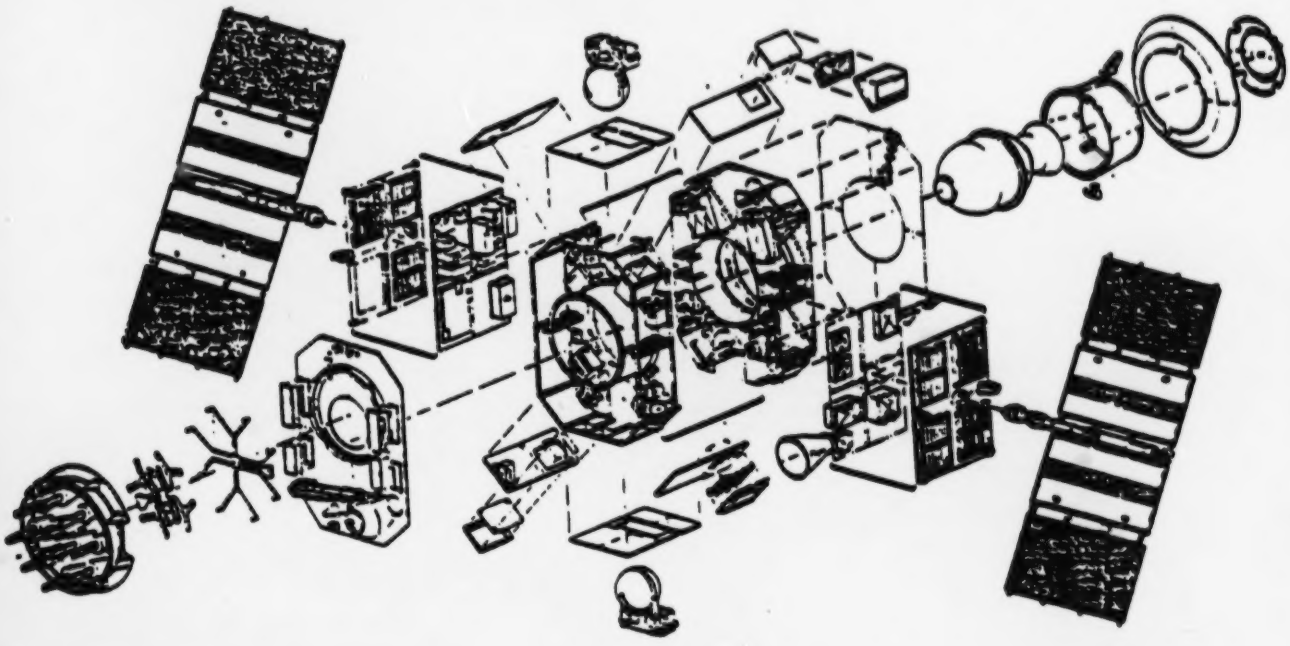
By awarding a single billion dollar multi-year contract for the 28 satellites, it is expected to result in a savings of more than $200 million for the acquisition of the satellites and about 1.5 years in the production schedule compared to purchasing the same number of satellites through annual procurement cycles.

When the GPS system is fully operational, there will be 18 satellites in six orbital planes. In addition, a Navstar satellite will be placed in every other orbital plane to serve as in-orbit spares. In the event of the loss of an operational satellite, the in-orbit spares can be moved in their respective orbital planes to maximize coverage on Earth. The in-orbit spares will be active thereby increasing the number of operational satellites in orbit to 21 during normal operations. Four of the remaining satellites will serve as ground spares and three are being built to replace any of the satellites lost during launch.

Figure 10 is an exploded view of the Block II satellites. The satellites are approximately 60 percent heavier than the prototype satellites to accommodate increased operational capacity. The increased capacity includes:

- Space Shuttle launch capability
- on-board diagnostics to sense system failures
- ability of the navigation unit to restore itself automatically and continue operation in the event its processors are upset by nuclear detonations
- ring-shaped antenna to detect nuclear detonations

The orientation of the satellite will be maintained by rapidly rotating momentum wheels and small rocket motors so that its navigation antennas will always be



SATELLITE CHARACTERISTICS

- WEIGHT WHEN DEPLOYED BY SPACE SHUTTLE = 3,675 LB
- WEIGHT AT INSERTION INTO FINAL ORBIT = 1,862 LB
- SOLAR ARRAYS (DEPLOYED) = 87 SQ FT
- DESIGN LIFE GOAL = 7.5 YR
- LIFE OF CONSUMABLES = 10 YR

STRUCTURE

- ALUMINUM HONEYCOMB PANELS
- COMPOSITE FACE SHEET HONEYCOMB PANELS
- SHORT RIGID LOAD PATHS
- ULTIMATE LOAD FACTOR 1.4 X LIMIT LOAD
- DYNAMICS FUNDAMENTAL
  - LAUNCH 16 Hz
  - ON ORBIT 0.4 Hz
- MAJOR AXIS SPINNER
- INTEGRAL BOX STRUCTURE
- THRUST CONE/CYLINDER
- 21 ft^2 RADIATING AREA

NAVIGATION PAYLOAD

- HARDENED NAV DATA UNIT
- FREQUENCY SYNTHESIZER DIST UNIT (FSDU)
- RUBIDIUM FREQUENCY STDS
- CESIUM FREQUENCY STDS
- 14 DAY NAV STORAGE
- ANTI SPOOF
- SELECTIVE AVAILABILITY
- NDS DATA DENIAL

AVCS

- PASSIVE NUTATION CONTROL
  - SPIN STABILIZED MODE
- ACTIVE NUTATION CONTROL
- PAM-D II DEPLOYMENT MODE
- 2.5 YEAR SPIN ON-ORBIT STORAGE MODE
- DIGITAL MECHANIZATION
- REACTION JET CONTROL
  - ATTITUDE MANEUVERING
  - MOMENTUM DUMP

TT&C

- OMNIDIRECTIONAL COVERAGE
  - FWD CONICAL SPIRAL & BICONICAL HORN
  - AFT CONICAL SPIRAL
- NON COHERENT
- COMMON RECEIVER/ TRANSMITTER ANTENNAS
- S-BAND SGLS UPLINK, DOWNLINK
- SIGNAL ENCRYPTION
- 0.5 & 4 K DATA RATES
- SHUTTLE INTERFACE

ELECTRICAL POWER

- 7.2 M^2 (77.58 ft^2) ARRAY
- 7-1/2 YEAR EOL 700 W SOLAR ARRAY
- 3 NICAD BATTERIES
  - 35 amp hr EACH
- 27 ± 1 Vdc BUS
  - DIRECT ENERGY TRANSFER
- SINGLE DEGREE OF FREEDOM SOLAR ARRAY
- SHUTTLE/PAM-D II POWER INTERFACE

L-BAND

- ANTENNA
  - SHAPED BEAM HELIX ARRAY
- SIGNAL GENERATION/TRANSMISSION
- RADIO ASTRONOMY BAND PROTECTION
- USER RECEIVED L-BAND SIGNALS
- SPREAD

  L1: — 160 dBw C/A & — 163.0 dBw P(Y)
  L2: — 166.0 dBw C/A OR P(Y)
  L3: — 165.2 dBw C/A

REACTION CONTROL SYSTEM

- HYDRAZINE PROPELLANT
  - 2 TANKS
  - ELASTOMERIC DIAPHRAGM
  - 22 THRUSTERS
- 2 MODULES
  - X, Y & Z AXES ΔV THRUSTERS
  - > 10-YEAR CONSUMABLES

GLOBAL BURST DETECTOR

- BLOCK I CONFIGURATION
- DATA DENIAL
- CROSSLINKED

INTEGRATED TRANSFER

- UHF (mil BAND)
- TDMA
- ANTI-JAM CAPABILITIES
- SPREAD

ORBIT INSERTION SYSTEM

- STAR 37XF SRM
  - TOTAL IMPULSE 526,670 lb sec
  - max. THRUST 10,600 lb
  - MECH SAFE & ARM
  - 28.5° ORBIT PLANE CHANGE CAPABILITY

THERMAL CONTROL

- 7 LOUVER PANELS
- 18 ft^2 LOUVERS
- CONTROL COATINGS
- MULTILAYER INSULATION
- TEMPERATURE CONTROLLERS
  - RUBIDIUM FREQUENCY STD
  - RCS, OIS & BATTERY
  - NAV COMPONENT

Figure 10 — Block II NAVSTAR Satellite

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pointing towards the Earth. Solar energy will be collected by photovoltaic cells mounted on over 77 square feet of solar panels to provide 700 watts of electrical power to the satellite. Three 35-amp-hour nickel cadmium batteries are located on each satellite to provide power for the satellite systems when the satellite is in the shadow of the Earth. The satellites have a design life of 7 1/2 years and contain enough rocket propellant to control its attitude for at least 10 years.

Each of the operational satellites continuously broadcasts on two different radio frequencies—L_1 and L_2 Superimposed on the L_1 are two uniquely coded signals. The C/A (clear/acquisition) code repeats every millisecond and is easy to acquire. The P (precision) code is more accurate than the C/A code. It is a sequence of digital signals that does not repeat itself for 267 days. Each satellite is assigned a unique 7-day portion of the code which it repeats every seven days. On the prototype satellites, the L_2 signal was modulated only with the P code. The L_2 signal on the operational satellites will be modulated with either the P code or C/A code which will be changeable on command from the ground. By broadcasting on two different frequencies, a correction can be made for the time delay as the signal passes through the ionosphere. This is the same reason that the Transit navigation system satellites broadcast on two different frequencies.

Key to the Navstar navigation satellite system is a highly accurate atomic clock which will gain or lose one second in 30,000 years. Atomic clocks are tuned to the vibrations of atoms or molecules which are extremely stable. On the prototype Navstar satellites, there were four redundant atomic clocks —three rubidium and one cesium—to insure that precise timing marks were always available. The operational satellites will have two rubidium and two cesium clocks. The rubidium clocks are smaller, lighter and require less power than the cesium clocks but are less sensitive.

All of the atomic clocks on the Navstar satellites are synchronized with the GPS system time which is maintained by a set of highly accurate cesium atomic clocks at the Master Control Station of the GPS system. The Master Control Station monitors the satellite clocks and transmits clock correction parameters to the satellite along with the navigation and system data. It should be noted that an atomic clock, which loses one second in 30,000 years, loses 100 nanoseconds a day. Radio signals travel at the speed of light (186,000 miles per second). In terms of navigation accuracy, the range error corresponding to a one nanosecond time error is approximately one foot. All of the satellite atomic clocks must be mutually synchronized to within two or three nanoseconds. Update messages are sent to the satellites as often as three times a day resetting their clocks to the required accuracy.

The control segment of the Navstar navigation satellite system is responsible for monitoring, updating the navigation messages and maintaining the exact position and clock accuracy records of the satellites in their respective orbits. It consists of a Master Control Station and a number of Monitor Stations and Ground Stations

located around the world (Figure 11). The Monitor Stations are unmanned data collection stations which are under the control of the Master Control Station. A GPS receiver is used to track all of the satellites in view and transmit the ranging data to the Master Control Station. In addition, the local temperature, barometric pressure and relative humidity are measured at the Monitor Station in order to determine the effect of the atmosphere on the range measurements.

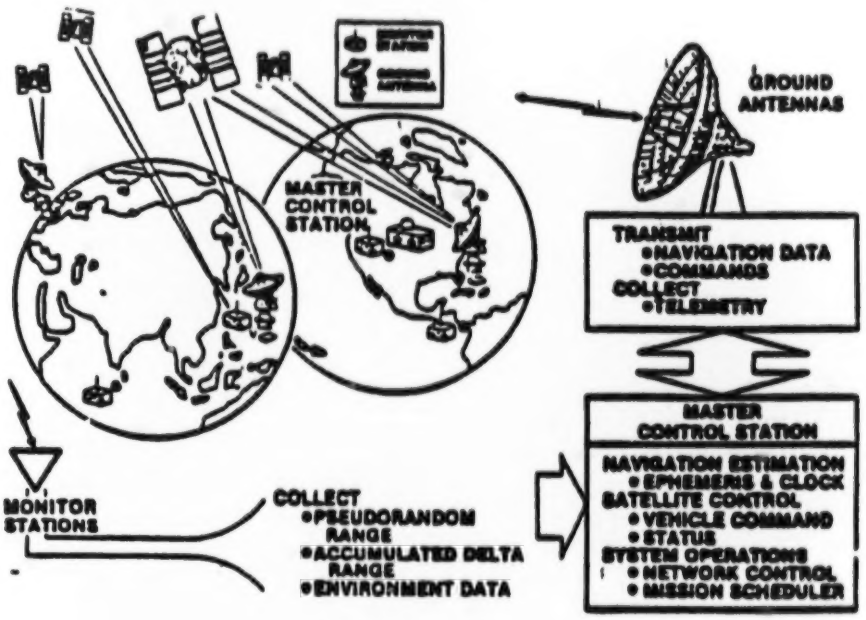

Figure 11 — GPS Control Segment

Since the location of each of the Monitor stations is known precisely, the Master Control Station uses the accumulated ranging data to determine the orbits of the satellites. The navigation message of each of the satellites is upgraded including the errors caused by ionospheric delay and the timing correction and transmitted to the satellites by the Ground Antennas. The Ground Antennas are also used for transmitting and receiving satellite control information.

During the validation phase of the GPS program, the Master Control Station and Upload Station were located at Vandenberg Air Force Base in California. Monitor Stations were located at Air Force bases in Alaska and Guam, and the Naval Communications Center in Hawaii. The final operational control center will consist of a Master Control Station, three Upload Stations, and five Monitor Stations. The Master Control Station will be located at the Consolidated Space Operations Center in Colorado along with a Monitor Station. Monitor Stations will be colocated with Upload Stations at Diego Garcia in the Indian Ocean, Kwajalein in the Pacific Ocean and Ascension in the Atlantic Ocean. The fifth Monitor Station will be lo-

cated in Hawaii.

The user segment is composed of a wide variety of user equipment designed to automatically lock onto the signals from the four most favorably located Navstar satellites and convert their signals into the three dimensional location of the receiver, its velocity and time. During the initial phase of the program, four contractors were selected to develop equipment which would meet the land-based, seaborne and airborne requirements of the Department of Defense. The four types of receivers developed during Phase I were a four-channel receiver, a one-channel receiver, a manpack receiver and a low-cost receiver. The low-cost receiver was designed to receive only the L_1 signal and the C/A code. The other receivers were capable of receiving both the L_1 and L_2 signals to eliminate the ionospheric refraction error as well as both the C/A and P codes.

The four-channel receiver was designed to operate in a highly dynamic environment (fighter aircraft and submarines) and where a fast navigation fix was required. The four channels tracked four satellites simultaneously to provide continuous navigation data.

The one-channel receiver was designed for a medium dynamic environment (helicopters, transport aircraft and surface ships) where operating time constraints and jamming levels were less stringent. The receiver was designed to be supplemented by other systems or instruments (inertial systems or altimeters) during periods of high dynamics or intense jamming. The receiver tracks and monitors four satellites sequentially one at a time.

The manpack receiver was a lightweight, one-channel receiver designed for a low dynamic environment such as a soldier-carried manpack or on trucks and tanks. It weighed less than 30 pounds, including batteries, and had a hand-held control indicator. The unit was designed not to be integrated with any other navigation system or instrument.

The low-cost receiver was a low-power, lightweight, one-channel unit. It was designed trading off performance with cost. The idea was to place a minimum accuracy receiver into use by the military services as soon as possible.

The Phase I development test and evaluation program of the user equipment was conducted at the Army's Yuma Proving Grounds in Arizona. Three ground-based laser trackers with a position accuracy of less than three feet and a velocity accuracy of better than 0.3 feet per second were made available to the GPS test program. This enabled an immediate comparison of the laser tracking position and velocity data with the corresponding data from the Navstar navigation satellite system. The Phase I test results are presented in Figure 12. The results correspond to 76 data missions on seven different types of vehicles using only three or four satellites in orbit. The overall results of seven meters (23 feet) at the 50 percent confidence level and 17 meters (56 feet) at the 90 percent confidence level met the

goals of the GPS program. The results of the low-cost receiver were of great surprise, as they were only a factor of approximately 2.5 less accurate than the four-channel receiver. It had been predicted that the low-cost receiver would result in position errors in excess of 100 meters (330 feet) at the 50 percent confidence level because it was using the C/A code and no correction for ionosphere effects was made. As a result, the Department of Defense decided to strictly control access to the P code and to degrade the accuracy available from the C/A code because of security reasons. Initially, the Department of Defense announced that it would degrade the C/A signal, renamed the Standard Positioning Service, to provide 200 meter (600 feet) at the 50 percent level and approximately 500 meters (1650 feet) at the 95 percent level. In 1983, the Department of Defense increased the accuracy available with the Standard Positioning Service to 40 meters (130 feet) at the 50 percent level and 100 meters (330 feet) at the 95 percent level. The Precise Positioning Service (P code) would be limited to United States and Allied military units and under certain conditions to non-military users in the United States.

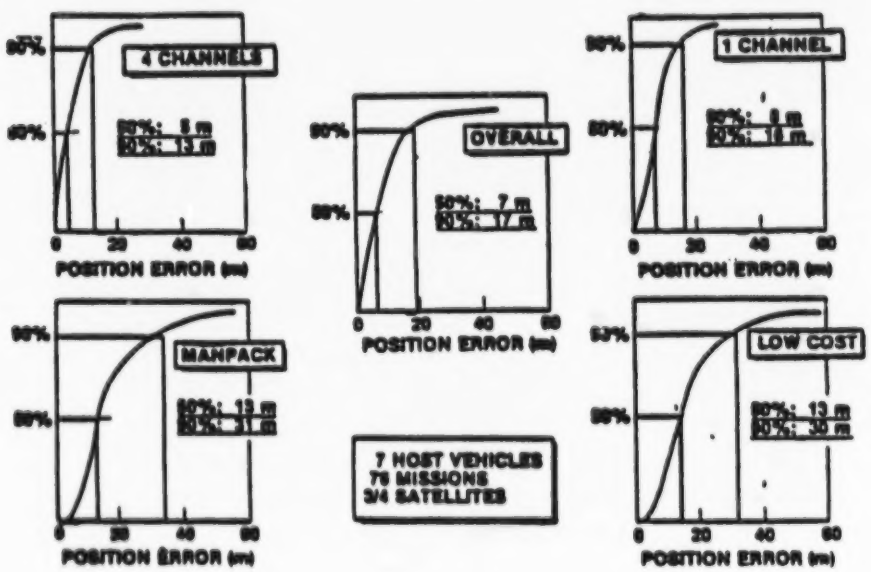

Figure 12 — Phase 1

In June, 1979, Magnavox's Government Electronics Division and Rockwell International's Collins Government Avionics Division were selected to continue the development of the user equipment during the full-scale engineering phase of the GPS program. The goal of the Phase II program was to develop smaller and lighter equipment which would have low life cycle costs, ease of integration into the host vehicle, increased jamming resistance and the capability to monitor the status of the hardware components. Both companies were given $75 million to design, build

and test 55 pre-production prototype sets of user equipment. In 1985, Collins was selected as the source for integration, development, and initial production of user equipment sets for the military services. The initial production contract is for over 6,000 sets of user equipment if all contract options are exercised.

System Operation

Each Navstar satellite broadcasts a navigation message on both the L_1 and L_2 signals which contains precise information about the location of the satellite and timing pulses. The timing pulses from all of the Navstar satellites are synchronized. By accurately measuring the time it takes for the timing pulse to travel from the satellite to the user equipment (Δt_1), the distance to the satellite can be determined since radio waves travel at the speed of light (C = 186,000 miles per second). The receiver must be located somewhere on a sphere of radius $R_1 = C \Delta t_1$, whose center is at the location of the satellite when it transmitted the timing pulse. If the user equipment measures the time it took for the same timing pulse to travel from a second Navstar satellite to the user equipment (Δt_2), then the receiver must also be located on a sphere of radius $R_2 = C \Delta t_2$ whose center is at the location of the second satellite when it transmitted the synchronized timing pulse. Since the user equipment must be located at points common to both spheres, it must be located somewhere along the intersection of the two spheres—namely, a circle. If the user equipment is on a Navy surface vessel, then it must be located at either of the two points where the circle intersects the Earth. Normally, one of the intersection points can be eliminated by knowing approximately where the vessel started from.

If the user equipment receives signals from a third Navstar satellite, then its location must be common to three spheres or at two unique points. Note that the intersection of the third sphere and the first sphere is a circle, and the intersection of two circles occurs at two points. In a three dimensional navigation fix, one of the points can normally be eliminated by altitude considerations.

It would appear from the above discussion that only three Navstar satellites are required to obtain a three dimensional navigation fix. However, since the clock on the user equipment is a quartz standard clock and less accurate than the atomic clocks on the satellites, it is necessary to receive signals from a fourth satellite to determine the clock bias (CB) on the receiver equipment. An error of one nanosecond in the synchronization of the satellite atomic clocks and the users quartz clock results in a range error of approximately one foot.

Figure 13 shows the method for the determination of the position of a helicopter and the user equipment clock bias using the Navstar navigation satellite system. In the figure, the location of the helicopter is given by the coordinates U_x, U_y, U_z. The location of Satellite 1 at the time the timing pulse was transmitted in the navigation message is X_1, Y_1 and Z_1 . The geometric range of the satellite from the helicop-

ter is given by the algebraic equation

$$\sqrt{X_1\text{-}U_x)^2 + (Y_1\text{-}U_y)^2 + (Z_1\text{-}U_z)^2}$$

The corresponding range in terms of the time it takes for the timing pulse to reach the helicopter (Δt_1) and the clock bias (C_B) is

$$C \Delta t_1 - C_B$$

Therefore

$$(X_1\text{-}U_x)^2 + (Y_1\text{-}U_y)^2 + (Z_1\text{-}U_z)^2 = (C \Delta t_1\text{-}C_B)^2$$

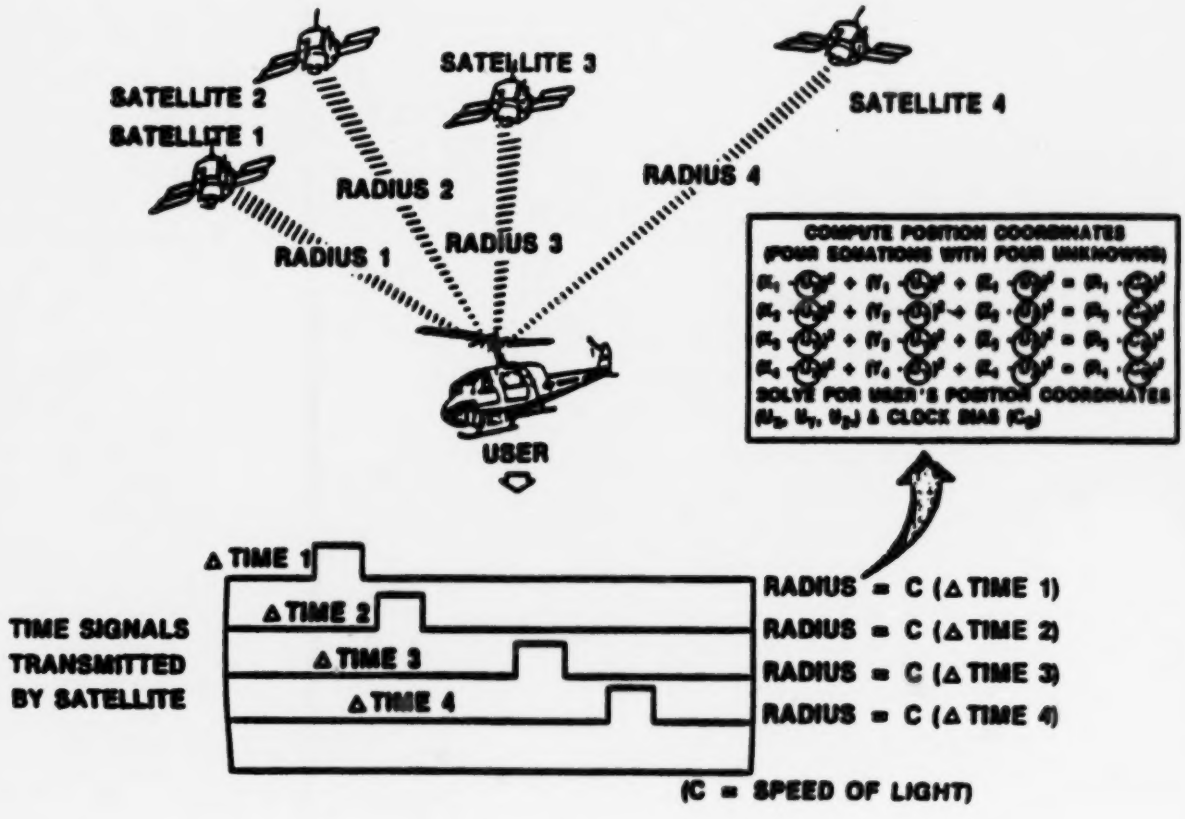

Figure 13 — Navigating with GPS

The position of the helicopter and the clock bias are determined by the solution of four simultaneous algebraic equations using the processor on the user equipment. The results are displayed as latitude, longitude, and altitude of the helicopter. All GPS position results are based on the World Geodetic System 1972 datum. It is stored in the receiver processor and provides data about the actual geometry of the land and sea (Geoidal Height Map).

The velocity measurements are made by measuring the Doppler shift of the L_1 and L_2 signals from the satellite. Precision measurements are possible because of the accuracy of the navigation messages from the satellites and the fact that four satellites are being used simultaneously.

All of the frequencies and digital clock sequences on the Navstar satellites are derived from a 10.23 MHz atomic clock frequency standard. The L_1 signal of 1575.42 MHz is 154 times the clock frequency and is modulated by both the C/A and P codes. The L_2 signal of 1227.6 MHz is 120 times the clock frequency and is modulated only by the P code during normal operations. For special application and testing, the L_2 signal can be modulated only by the C/A code. Both frequencies are transmitted simultaneously to correct for the effect of the propagation of the signals through the ionosphere. The user equipment generates C/A and P codes that are automatically compared to the codes being transmitted from the satellite. When the codes match, the receiver locks onto the signal. The time increment that the signals are out of phase is equal to the time it takes for the signal to travel from the satellite to the receiver.

Over six trillion digital signals are transmitted before the P code is repeated on a given satellite. As a result, it is extremely difficult for a receiver to lock-on the P code unless it knows fairly accurately what region of the code to search. The C/A code was designed to assist a user in reducing the time necessary to match and lock-on the P code.

The navigation message, which is modulated onto the L_1 and L_2 signals, provides the user with the data required to determine a navigation fix. The message is 30 seconds in length and consists of five data subframes. The second word in each frame is a handover word (HOW) to permit the transfer from the C/A code to the P code. It alerts the receiver to the time synchronization of the P code at the next HOW six seconds later at which time the code transfer would take place. The remainder of the message contains information about the satellite's orbit, the satellite clock correction, the ionosphere model for correcting the refraction error, the status of the satellite and almanac data on the position of all of the Navstar satellites as a function of time.

Applications

The Navstar Global Positioning System is designed to provide multiple users with an accurate, continuous, world-wide, all-weather three-dimensional positioning

and navigation capability. During the Phase I testing of user equipment sets, many military applications of the GPS system were demonstrated and evaluated, including precision weapon delivery, rendezvous between aircraft and shipboard operation. Figure 14 lists some of the projected military applications of the GPS system.

En-route Navigation
Low-level Navigation
Target Acquisition
Close Air Support
Missile Guidance
Command & Control
All-Weather Air Drop
Sensor Emplacement
Precision Survey
Space Shuttle Navigation
Ionds
Instrument Approach

Rendezvous
Coordinate Bombing
Remotely Piloted Vehicle Operations
Barebase Operations
Search & Rescue
Photo-Reconnaissance
Elint Annotation
Satellite Tracking & Navigation
Range Instrumentation
Inertial Update
Mine Emplacement & Countermeasure

Figure 14 — GPS Military Applications

The Department of Defense plans to purchase approximately 20,000 sets of user equipment by the year 2000. Because of the three-dimensional capability of the GPS system, almost 80 percent of the units will be installed in aircraft and helicopters. To demonstrate the accuracy of the GPS system for aircraft navigation, Collins Avionics flew a company Sabreliner from its plant in Cedar Rapids, Iowa to the Paris Air Show in May, 1983, using only the Navstar system. During the flight there were only five prototype satellites in operation. Since the satellites could only be used by the aircraft for several hours at a time for navigation fixes, it was necessary for the Sabreliner to land when four Navstar satellites were not in view simultaneously. As a result, the trip from Cedar Rapids to Paris took four days with intermediate stops in Burlington, Vermont; Gander, New Foundland; Reykjavik, Iceland and London, England. During the flight, the aircraft kept within 150 feet of its planned course. In addition to the GPS user equipment, the Sabreliner carried an inertial guidance system and an Omega receiver. These systems showed position errors during the flight by as much as 8.7 and 13 miles, respectively. When the aircraft landed at Le Bourget airport, the pilot was not given any information as to the aircraft's parking location by ground personnel. Using the GPS system only, the Sabreliner came to a stop within one wingspan of its predesignated parking spot. If the Korean Airline Boeing 747 which was shot down over the Soviet Union on September 1, 1983, had been carrying a similar GPS receiver. to update its inertial guidance system, it may not have strayed off its course. The Federal Aviation Administration (FAA) is studying the possibility of using the GPS as the primary navigation system on aircraft when it becomes fully operational in the mid-1990s.

Figure 15 shows some of the civilian applications of the Navstar Global Positioning System. Many of the civilian applications are similar to those of the Department of Defense. Although there are only eight prototype satellites in orbit in 1986, civilian user equipment sets are available from Collins Avionics, Magnavox, Raytheon, Texas Instruments and Trimble Navigation. However, the United States government has issued a notice in the Federal Register that until the GPS system is declared fully operational, civilian use of the satellite signals is strictly at the users risk. As part of the research and development program of GPS, the signals may be changed without warning or may be turned off or on at any time.

Figure 15 — GPS Civil Applications

Although there are three or more satellites available for navigation fixes for only 7 to 10 hours per day at a given location, marine GPS user equipment is available at a cost of between $17,500 and $25,000—7 to 10 times the cost of Transit receivers. A typical GPS receiver provides automatic satellite acquisition and tracking, two or three dimensional fixes, and route to destination with 30 waypoints via Rhump Line or Great Circle Routes. The accuracy of the Magnavox receiver is quoted as "35 meters with 90 percent probability when 3 or more GPS satelites are visible. Actual GPS performance is dependent on satellite and control segments. The United States government may limit GPS accuracy to 100 meters when the GPS system is fully operational." Because of the limited period of time during a day that the GPS system can be used, many of the receivers are interfaced with Loran or Transit receivers.

One of the most interesting applications of the GPS system is for land navigation and positioning. As an example, the Burlington Northern Railroad Company uses two techniques for determining the location of a train along its route. The train engineer can observe the number on a milepost and radio it to a dispatcher. The other technique is to use track sensors at a cost of $60,000 per mile which automatically sends the location of the train to the dispatcher.

In 1985, Burlington Northern Railroad installed Collins Avionics' receivers on two locomotives. The equipment determines the location of the train using the Navstar satellites which is then radioed to the dispatcher by the engineer. It is expected that the system will reduce delays and improve fuel efficiencies. In the future, Burlington Northern plans to input the navigational data into a computer on the train which contains topographical data about the train route. The computer will then determine the train velocity to obtain the best fuel efficiency.

In the fall of 1981, the Honda Motor Company announced the development of an automobile navigation system called the Electro Gyro-Cator. The system is an inertial navigation system that displays the location of the vehicle on a 5-inch by 6-inch video display unit mounted on top of the dashboard.

When using the navigation system in a particular region, a transparent color map of the region is laid over the video screen. The initial location and direction of travel are entered into the system's microprocessor and displayed on the screen by a cursor symbol. As the automobile moves, the tire rotation is measured by a magnetic detection sensor to determine the distance traveled. The direction of travel is measured by a directional sensor which contains a self-calibrating gyroscope. The information from both sensors is fed into the microprocessor to determine the path of the vehicle and display it on the screen. The video display remains off when the automobile is moving as a safety feature. The driver can determine his location on the screen when the automobile comes to a stop at a traffic light or in heavy traffic. A passenger in the front seat of the Honda can keep the display unit on if he so desires.

The Honda navigation system is available only in Japan at a cost of $1,100. One of the disadvantages of the system is that the errors, which includes those due to the variation of tire radius, are cumulative. This can be offset on a long trip by updating the position of the vehicle at known points along the route.

As part of its program to evaluate navigation aids for the motorist of the future, General Motors installed GPS user equipment in a 1983 Buick Park Avenue. The position of the vehicle, as determined by the GPS receiver, is displayed on a color, 9-inch diagonal cathode ray tube mounted in the center of the instrument panel. The receiver was designed by Collins Avionics to GM specifications and is located in the trunk of the Buick along with the display computer. The signals from the Navstar satellite are picked up by a small antenna approximately 3.5 inches in length and 0.75 inches in diameter. The antenna is located on top of a conventional retractable automobile antenna.

In using the system, a magnetic tape cartridge containing digitized U. S. Geological Survey maps is inserted into a slot in the dashboard. The display computer correlates the position data from the GPS receiver with the digitized display map. The location of the Buick is displayed as a small flashing rectangle. As the car

moves, the flashing rectangle leaves a blue trail to indicate the route taken. On the map major highways are marked in purple, secondary roads in yellow, and state boundaries are multicolored. When the flashing rectangle reaches the edge of a map displayed on the cathode ray tube, a new map automatically appears on the screen.

In the trip-planning mode, a driver is able to input into the display computer the origin and destination of a trip as well as intermediate stopping points. As the trip progresses, this information is displayed on the map. The distance and relative bearing to each stopping point can be displayed at the touch of a button. The driver has the option of increasing the level of detail of the maps displayed during a trip. As the car approaches the final destination point, the map with the greatest level of detail is automatically displayed.

The demonstration vehicle is also equipped with a Loran-C receiver and a compass and odometer for dead reckoning. When four Navstar satellites are not in view of the Buick antenna simultaneously, Loran-C is used in conjunction with the display unit to evaluate the system for automobile navigation. When both radionavigation systems are not available for use, the compass and odometer are used to determine the path of the Buick and display it on the cathode ray tube.

The Chrysler Laser Atlas Satellite System (CLASS) was introduced at the New Orleans World's Fair in 1984. The major difference between the Chrysler system and the GM system for automobile navigation is the manner in which the maps are displayed on the cathode ray tube.

In the CLASS system, maps are stored on an eight-inch optical disc. Over 25,000 individual frames of graphic, pictorial, or printed data can be sorted on the disc in full color. The system was demonstrated with 13,249 full color American Automobile Association road maps, which cover the United States with maps scaled from 50 to 3200 square miles. The remaining frames on the disc can be used for photographs of points of interest or information about hotels, resorts and restaurants.

When the system is turned on, the display computer automatically displays a map showing the car's location. The location of the car is represented by a Chrysler Pentastar. As the Pentastar approaches the edge of the map, the display computer automatically selects the adjacent map and displays it. The driver can change the scale of the map by merely touching the screen.

The GPS system can also be used for land surveying and offshore oil exploration. During the fall of 1986, the accuracy of receivers manufactured by three different companies was determined. In a park across from the San Francisco Civic Center, a set of GPS receivers was located 100 feet apart. From the signals from the Navstar satellites, the separation distance between the receivers was determined to within 0.3 inches in all three tests. Scientists believe that the GPS system will provide an

accurate, inexpensive, and rapid method for determining the movement of the tectonic plates which make up the Earth's crust and the resultant changes in the height of the Earth's surface.

By the year 2000, it has been projected that civilian user equipment will be available for as little as $500. Civilian users of GPS receivers will far exceed the number of military users. Small hand-held units will be available for campers, hikers and hunters, enabling them to explore unfamiliar areas. Differential GPS transmitters will be installed at small airports to improve the local navigation accuracy in all types of weather. Surveying equipment based on the Global Positioning System will be available to map uncharted areas. Preprogrammed routes on truck navigation systems will save time and money for trucking companies on long distance routes. The Navstar Global Positioning System is extremely versatile and there will be many other applications for it in the year 2000.

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